Magellan Aerobrake Navigation

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The Magellan spacecraft has been aerobraked into a 197 x 541 km near-circular orbit around Venus from which it is conducting a high-resolution gravity mapping mission. This was the first interplanetary aerobrake maneuver and involved flying the spacecraft through the upper reaches of the Venusian atmosphere 730 times over a 70 day period. Round-trip light-time varied from 9.57 to 18.83 minutes during this period. Navigation for this dynamic phase of the Magellan mission was planned and executed in the face of budget-driven down-sizing with all spacecraft safe-modes disabled and a flight-team one-third the size of comparable interplanetary missions. Successful execution of this maneuver, using spacecraft hardware not designed to operate in a planetary atmosphere, demonstrated a practical cost-saving technique for both large and small future interplanetary missions.

1.0 INTRODUCTION

The Magellan spacecraft has been orbiting Venus since August 10, 1990. Its primary mission has been to radar-map the Venusian surface. Over 98% of the planet has been observed at resolutions between 120 and 300 meters. With an axial rotation period of 243.01 days, Venus rotated beneath the spacecraft's 3.25 hour, inertially fixed orbit three times during the radar-mapping phase, providing comparison scans at 8 month intervals. 4796 radar-mapping passes were made. Initial Magellan science results have been collected in reference [1]. Navigation during the 462 day flight to Venus and the first 20 months of mapping are discussed in references [2-4].

After the third radar cycle, with high-rate radar data no longer available due to progressive deterioration of X-band subcarrier modulation, a gravity mapping mission was begun. Spacecraft periapsis was lowered from 258 km to 185 km. This maneuver enhanced gravity field determination, thus knowledge of the planetary interior, by moving the spacecraft closer to Venus' irregularly distributed mass.

Spherical harmonic gravity field models of degree and order 21 had been developed and iteratively improved by the navigation team throughout the mission [5], but were inadequate for detailed structural analysis. A separate Gravity Investigation Group began using Cycle-4 two-way X-band (8.4 GHz) Doppler data to develop a 60 x 60 gravity model.

Both types of mapping were conducted from a near-polar, elliptical orbit whose general shape is shown in fig. 1. Eccentricity typically varied between 0.392 and 0.4 due to perturbations described below. The ellipticity affected mapping activities since the spacecraft began a mapping pass at an altitude of 2200 km over the North Pole. Altitude then decreased to the 260 km periapsis minimum before increasing to 3400 km over the South Pole. The radar system compensated for rapidly changing range and slant angles by using uplinked navigation data to adjust its operating parameters over 3000 times in a given 25 minute mapping pass, but useful passive gravity mapping was limited to the +-30 degree true anomaly region centered on the 10 degree North periapsis latitude.

To improve gravity field resolution at high latitudes, it was necessary to lower the altitude over the poles by reducing the apoapsis altitude, thus making the orbit more circular. Over 900 kg of fuel would have been required to do this propulsively. Magellan had only 94 kg on-board, requiring the use of some other method.

2.0 What is Aerobraking?

Using atmospheric drag to circularize Magellan's orbit has been considered since the 1980's [6-7]. Detailed plans for a relatively conservative Magellan aerobrake were being developed in 1991, but were shelved when mission finances decreased in January 1992, reducing flight team staffing levels to one-third that of the primary mission. The option was subsequently revived in September, 1992 and reworked into a high risk mission that lacked normal operational safety margins made possible by typical funding and manpower.

Aerobraking uses friction caused by passage through a planetary atmosphere to provide a velocity change at periapsis. The force component opposite the direction of spacecraft motion (drag) causes a decrease in apoapsis altitude by reducing the total energy of the spacecraft through frictional dissipation. Analytical

approximations can expose the mechanics of this process and informative derivations may be found in reference [8].

For highly eccentric orbits, periapsis altitude is only slightly affected by a drag pass. Therefore, one consequence of repeated drag passes is a contracting orbit that spirals in toward the planet as apoapsis altitude decreases and periapsis altitude remains roughly the same. Fig. 1 shows this circularization process.

Network (DSN) tracking stations.

Specified parameters (such as position and velocity) are then statistically estimated using a least-squares batch square-root information filter. There is extensive literature on the mathematical basis of parameter estimation theory. Interested readers are referred to items [9-10] in the bibliography.
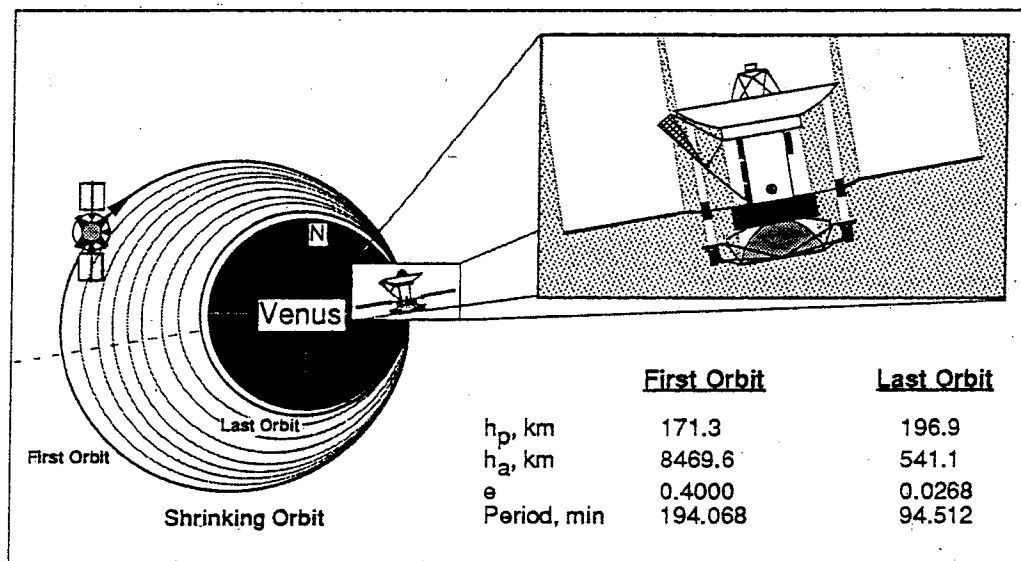

	First Orbit	Last Orbit
h_p, km	171.3	196.9
h_a, km	8469.6	541.1
e	0.4000	0.0268
Period, min	194.068	94.512

Fig. 1   Magellan transition to near-circular orbit. Drag-pass cross-sectional surface is shown center-left. "h_p" is the periapsis altitude, "h_a" the apoapsis height. "e" is eccentricity.

Many orbiters are eventually affected by drag in this way, prior to re-entry and disintegration. An aerobrake seeks to control drag deceleration and deliver an operating spacecraft to a desired orbit from which additional mission objectives may be met.

3.0   Magellan Navigation

In addition to drag, other cumulative and periodic forces act on the spacecraft, constantly altering the shape and orientation of the orbit in space. Major perturbing forces are listed in Table 1, along with additional model parameters necessary to describe radio signal propagation and measurement geometry.

The navigation team models these forces numerically using the DPTRAJ/ODP software set developed and maintained by the JPL Navigation Systems section. A nominal trajectory is integrated, over some time interval in which observations have been made, using initial conditions and force models established by the navigation team.

The actual trajectory will deviate from this nominal prediction due to random disturbances and model approximations. The deviation is quantified when residuals are formed by subtracting the model-predicted frequency-shift from actual measurements made by the Deep Space

Predicted residuals based on the newly estimated parameter set are then computed, quantifying the difference between the new trajectory, based on the newly estimated parameter set, and the original nominal trajectory. Numerical models may be adjusted, if warranted, and the data edited and weighted to reduce the size of predicted residuals, thus improving estimated parameter knowledge. Various techniques and several iterations may be necessary to optimize residuals. Residuals of zero magnitude would indicate perfect knowledge of spacecraft motion and perfect measurements.

Knowledge of the spacecraft's orientation in space (attitude), is maintained by the spacecraft itself, under the supervision of the Martin Marietta-Denver spacecraft team. Magellan performs star-scans every other orbit to autonomously update its two-remaining on-board gyroscopic inertial reference units. The navigation team models spacecraft orientation, to account for solar pressure, thruster activity and drag, but has the different responsibility of originating and maintaining knowledge of the spacecraft's center-of-mass and predicting its position in the future.

Navigation analysis and operations were performed numerically on a dedicated computer network composed of one 102 MIPS Sun/Sparc 10, a 28.5 MIPS Sparc 2, a Sun 3/260 and three Sun 3/60s running Unix, with 6.5 gigabytes of on-line hard-disk storage.

TABLE 1: MAGELLAN AEROBRAKING MODEL SUMMARY

Venus Gravity	- a_e = 6051.0 km - Reference field = 21x21 JPL-MGN05
Perturbations and Relativity	- Newtonian point mass sun, moon, planets (JPL DE200 ephemeris and masses) - Relativistic effects due to the Sun
Solar Tides	- Venus k_2 = 0.255
Atmospheric Drag	- LST-varying static exponential model - $\rho = \rho_0 \exp[(h_0 - h)/H]$ - Base density (ρ_0); solved for parameter - Base altitude (h_0) = 131 km - Scale height (H) = '79-80 VIRA [*Keating*] - Drag pass effective spacecraft area = 23 m^2 - Mass = 1128.8 to 1091.0 kg
Solar Radiation Pressure	- Spacecraft bus, solar panels, and antenna modeled (flat plates, parabolic antenna) - Spacecraft orientation modeled
Venus Rotational Parameters	- Rotation rate = -1.4813291 deg/day - Pole right ascension (J2000) = 272.69 deg - Pole declination (J2000) = 67.17 deg - Prime meridian (J2000 Epoch) = 160.39 deg
AACS Thrusters	- 600 sec constant accelerations (solved for)
COTM Maneuvers	- Finite burns; 1-n = 50.6 sec, 2-n = 101.2 sec
DSN Station Locations	- SSC(JPL) 91R01 rot. 1993.5/DE200 [*Folkner*]
Clock Calibration	- GPS/DSN determined; Nav LS fit (daily)
Ionosphere Calibrations	- Faraday rotation/GPS measurements (daily)
Troposphere Calibrations	- Wet/dry seasonal model [*Chao*]
UT1/Polar Motion	- GPS determined values (updated weekly)

4.0   Navigation Data

Two types of tracking data were available for this purpose during aerobraking: two-way coherent S-band (2.3 GHz) Doppler and S-band differenced Doppler. The more accurate measurements provided by the higher-frequency, lower-noise X- band transponder were unavailable during aerobraking. It was necessary that the rigidly-fixed high-gain antenna, with its 20-watt X-band and 5-watt S-band beam-widths of 0.6 and 2.2 degrees respectively, usually be pointed either toward the Sun, for thermal relief, or opposite the direction of motion during a drag pass for aerodynamic stability. Thus, the primary source of Doppler tracking data was expected to be the medium-gain, 5-watt S-band telemetry antenna (18 degree beam-width). Less than 10 minutes of HGA S-band data were available each orbit.

To make two-way Doppler measurements, a very stable uplink carrier frequency is established. The spacecraft is equipped to return ("transpond") a downlink frequency at a precise multiple of the uplink frequency. This signal is also received at the transmitting site where it is differenced with the uplink frequency to provide an instantaneous measure of the frequency change due to the relative motion of the tracking antenna and the spacecraft. This Doppler shift is a direct measure of the line-of-sight relative velocity and can be expressed in either frequency (Hertz) or velocity (mm/s) units. X-band Doppler can measure velocity to a 0.1 mm/s noise level. S-band measurement accuracy is dependent on whether the spacecraft is using its high or medium-gain antenna, but is generally good to 1 mm/s or better.

This Doppler measurement is a convenient by-product of establishing a radio link with the spacecraft. Telemetry and science data are encoded on the same signal. The sinusoidal carrier wave is phase modulated, creating a superimposed signal that is also periodically varying in frequency. Telemetry and science data are modulated onto this "sub-carrier" rather than the main carrier. Since Doppler shift occurs slowly compared to telemetry and science data, the signal may be averaged over some time interval to eliminate frequency variations due to data transmission. In practice, Magellan tracking data took the form of discrete "points" representing a 60-second average of a continuous Doppler frequency-shift measurement. During the last month of aerobraking, 10-second averaged tracking data was used to improve determination of the rapidly changing orbit.

The second data type, differenced Doppler, complements two-way Doppler by measuring velocity in the plane-of-sky; perpendicular to the line-of-sight direction measured by two-way Doppler. This is accomplished by differencing two-way Doppler measurements with three-way measurements.

During periods of overlapping station coverage, while one DSN tracking station has a two-way lock with the spacecraft, a second DSN tracking station can simultaneously monitor the spacecraft's transmitter. By differencing these three-way measurements with the two-way measurements, it is possible to cancel geocentric components of spacecraft motion, as well as delay effects due to signal interaction with solar plasma, while reducing the sensitivity of the orbit determination process to dynamic mismodeling [4].

Three baselines are available for the DSN to make these measurements: California-Australia, Australia-Spain, and Spain-California. When measurements from one or more of these baselines are combined with two-way Doppler, the spacecraft state is generally observable when coupled with the dynamic models needed to infer position from velocity measurements.

5.0   Aerobraking Overview

Since Magellan hardware was not designed to operate in a planetary atmosphere, three basic constraints defined the flight team's approach to aerobraking. The first was a 180 C maximum temperature limit on the high-gain antenna and a 179 C limit on solar panel diode solder, although the solar panel temperature sensor stopped at 160 C [11]. This limited the speed with which aerobraking could be conducted before the antenna's graphite/epoxy laminate surface risked debonding or the diode failed. Analysis by the spacecraft team at Martin Marietta and space shuttle experimentation (STS-46) with Magellan materials in a high-velocity atomic oxygen environment indicated these would be the most threatened components.

The second constraint was that aerobraking be completed within 80 days. Visible star-pairs for the aerobraking star-scan attitude update procedure were unavailable beyond that point. DSN contention with other tracking intensive projects, including the Mars Observer Orbit Insertion and the Galileo Ida asteroid flyby was an additional consideration. It was also desirable to conduct aerobraking in the day-side atmosphere of Venus due to smaller day-side density variations. Data from Pioneer-Venus and previous Magellan cycles indicated a 1-sigma orbit-to-orbit density uncertainty of 10% on the day-side atmosphere (at 180 km) versus a 50% 1-sigma density uncertainty on the night-side. Magellan's periapsis point, moving 6 minutes and 24 seconds of Venus local solar time (LST) later each Earth day, would be approaching the night-side by early August. Thus, risk to the spacecraft would be reduced if the maneuver was completed by that time.

The third constraint was the need for a final orbit with a period greater than 94 minutes so that solar panels would be able to track the Sun and maintain adequate spacecraft power levels. An exactly circular orbit would require extensive maintenance, primarily due to solar and Venus gravity field perturbations, while offering only a minor improvement in gravity science return compared with a more stable, near-circular orbit (the rule-of-thumb is that gravity field resolution is approximately the same as the altitude). An initial target orbit was thus 250 x 550 km, but the final-orbit decision was held for the last week of the maneuver, before exiting the atmosphere.

The primary factor that served to locate the aerobraking start date was the desire to fully complete the Cycle-4 gravity mapping mission, from its 180 x 8500 km

orbit, before attempting to aerobrake closer to the planet. Aerobraking was targeted to begin May 25, 1993, when the spacecraft periapsis was at 10:30 a.m. Venus LST, and conclude no later than the 2nd week of August, as LST approached 6:30 p.m.

5.1 Dynamic Pressure

These constraints led to the selection of dynamic pressure as a driving parameter during aerobraking. Closely related to component temperature, dynamic pressure is equal to half the atmospheric density multiplied by the square of the spacecraft velocity. This quantity could be determined by the navigation team through analysis of the radiometric tracking data.

Studies by the Mission Planning and Spacecraft teams indicated an upper dynamic pressure limit of 0.32 N/m^2 was compatible with component temperature constraints, allowing for likely maximum density variability. This effectively defined a dynamic pressure "corridor" in which efficient aerobraking could occur. If dynamic pressure substantially exceeded 0.32 N/m^2, critical component temperatures could be surpassed. This could potentially destroy the spacecraft. If aerobraking was conducted at too low a dynamic pressure, it would be inefficient and take more than 80 days to complete.

The goal of the flight team was to operate within this dynamic pressure corridor so as to conduct an efficient and timely aerobrake to the desired orbit without destroying critical components through over-heating. All safe-modes were disabled due to lack of operational support, meaning a hardware or software failure would result in loss of the spacecraft.

5.2 Maneuvers

Positioning within the corridor would be maintained by the use of "Corridor Orbit Trim Maneuvers" (COTMs). These were six selectable maneuvers that were developed before the start of the aerobrake and resided on-board the spacecraft at all times during the aerobrake. A nominal burn, called "1-n", provided a 0.34 m/s velocity change. There was also a "1/2-n" maneuver and a "2-n" maneuver, providing 0.17 and 0.68 m/s of delta-v respectively. These values decreased somewhat as aerobraking progressed due to decreasing propellant tank pressure.

Two variations of each maneuver existed; an up and a down version. By executing the appropriate maneuver at apoapsis, periapsis altitude could be adjusted up or down according to the magnitude of the selected burn. This allowed the spacecraft to be maneuvered within the dynamic pressure corridor so as to adapt to unpredictable atmospheric conditions such as sudden increases or decreases in density at a given altitude. At the start of aerobraking, the 1-n burn changed periapsis altitude by 1.6 km, 1/2-n by 0.8 km, 2-n by 3.2 km. Maneuver opportunities occurred every other apoapsis and could be commanded or disabled on 2 hours notice, although an 18-hour lead time was normal. The intervening apoapsis was reserved for a star-scan attitude update.

The Mission Control Team's Magellan ACE had the option of autonomously commanding an "emergency" OTM maneuver (EOTM) at the next apoapsis, if real-time telemetry indicated the spacecraft was in imminent danger. This exit maneuver would also be used to terminate aerobraking by raising periapsis out of the atmosphere and circularizing the orbit.

During a periapsis drag pass, the spacecraft would be aligned with its high-gain antenna pointing opposite the direction of motion (trailing the spacecraft bus) for aerodynamic stability. Solar panels would be perpendicular to the flow, maximizing cross sectional surface area at 23 m^2. The drag coefficient, C_d, was taken to be 2.2 for this free molecular flow regime.

To prevent spacecraft tumbling due to unbalanced aerodynamic torques about the center-of-mass, attitude control thrusters were fired during drag passes to counteract the torques (Magellan otherwise used reaction wheels for attitude control). Because of the thruster-first drag-pass attitude, thrust opposed spacecraft motion, acting like a drag deceleration asymmetrically applied around periapsis, speeding the aerobrake process while tending to rotate the line of line-of-apsides. These small firings contributed between 10 and 120 mm/s of velocity change at each periapsis.

The exact times of these thruster pulses could not be reported to the ground due to spacecraft memory limitations. This significantly complicated orbit determination and prediction since there would be three largely unknown forces acting on the spacecraft at each periapsis passage: gravity field irregularities, atmospheric drag, and variable spacecraft thruster activities. Because of the drag-pass attitude, there was no tracking data for 30 minutes on either side of periapsis. Forces had to be resolved and statistically estimated using after-the-fact tracking data.

6.0 Planning Aerobraking Navigation

The primary aerobraking planning phase was between January and May of 1993. Principal navigation team tasks during this period were as follows:

• Update the input modeling of the Venusian atmosphere to incorporate a new multi-layer, time-varying static exponential model developed by Gerald Keating of NASA-Langley [12]. This initial model was based on Magellan data and low-altitude measurements made during the Pioneer-Venus controlled entry in October 1992, as well as PVO data from 1979-1980.

• Improve the navigational global gravity field by including tracking data from the Cycle-3 mapping phase in a newly estimated 21 x 21 field.

• Conduct covariance, sensitivity and Monte-Carlo studies, providing the resulting navigational capabilities to the other Magellan teams through error

bounds and timing uncertainties. Simulated tracking data was generated for different phases of the maneuver for testing and training purposes.

- Scope out entire aerobraking altitude and dynamic pressure profile for the aerobraking interval and recommend to the project the most desirable profile from a navigation stand-point.

- Conduct detail design of atmosphere "walk-in" maneuvers used to initiate aerobraking.

- Install and integrate a new Sun Sparc 10 Unix workstation into the navigation computer network.

- Establish "canned" corridor-control maneuvers to reside on-board the spacecraft throughout aerobraking. These maneuvers were designed by Cheick Diarra of the JPL's Navigation Systems maneuvers group and provided to the Magellan navigation flight team.

- Write special-purpose programs to expedite the navigation task and compute aerobraking-specific information such as drag-duration.

- Support daily Cycle-4 orbital operations.

A three-person staff was available for these activities, although this was temporarily reduced to two while the Team Chief recovered from a heart attack. During actual aerobraking operations, navigation staffing was increased to five. Planning and executing this highly dynamic mission phase with one-third the typical staffing levels was possible due to the entire flight team's extensive orbital operations experience; Magellan had been in a continuous planetary encounter mode for 2.5 years resulting in a high-level of confidence in nominal procedures and spacecraft capabilities. In addition, numerous software tools, Unix scripts and procedures had already been developed by the navigation team to automate those navigation tasks amenable to automation.

6.1   Phases of Aerobraking

Aerobraking had 4 primary phases [13]. The first 4 days were the "walk-in" phase. A series of maneuvers incrementally lowered periapsis altitude from the final Cycle-4 altitude of 171.3 km until the desired dynamic pressure corridor altitude was located [14-15]. This altitude was not well known in advance because of uncertain knowledge of atmospheric density below 150 km. The walk-in phase allowed sufficient time to characterize the atmosphere and adapt models to better match actual conditions below 150 km.

After Walk-In, the aerobrake Main-Phase extended for the next two months, until the end of July. This phase had two distinct divisions; up and down. In the first, periapsis altitude gradually decreased with repeated drag passes at the same time density increased due to solar heating near local Noon. This required compensating periapsis-raise ("up") type maneuvers to keep dynamic pressure within tolerance. Toward the middle of July,

"down" type COTMs would be required to maintain aerobraking efficiency, due to decreasing density caused by atmospheric cooling, as well as coincidental gravity perturbations which tended to raise periapsis at this time.

The End-Game phase began on July 27th. It defined the interval when the orbit would change most rapidly. Orbit period would be under 102 minutes so that the spacecraft would make 14-16 drag passes each day in an unstable atmosphere transitioning to night. The length of each drag pass would increase as the spacecraft cut progressively longer arcs through this atmosphere. After Walk-In, Magellan spent 520 seconds at altitudes below 250 km (sensible atmosphere). This would increase to over 2400 seconds in the End-Game. In addition, the unmapped gravity field near the poles was expected to begin strongly perturbing the spacecraft as the orbit wrapped more tightly around the planet.

The final Circularization phase would terminate aerobraking, once the desired apoapsis altitude was achieved. A thruster firing would lift periapsis out of the atmosphere. Additional burns would raise periapsis to the final altitude for the desired near-circular orbit.

6.2   The Atmosphere of Venus

Determining and adapting to conditions in the Venusian atmosphere below 150 km was important to the successful navigation. Data was available from Pioneer-12 1992 entry measurements, made as low as 129.1 km on the Venus night side, and Magellan Cycle-4 navigation density solutions between 170 and 180 km. Density results derived from Doppler tracking data were supplied to Keating and Hsu for incorporation into a new static exponential model of the Venusian atmosphere. This model also used density data derived from spacecraft torque measurements.

The high-frequency Magellan data (8 periapsis passages a day versus one a day for Pioneer-Venus) revealed a standing density wave at 170 km, with a 4-day period, due to the super-rotation of the atmosphere around the planet. Atmospheric composition at the aerobraking altitude was primarily atomic oxygen and carbon-dioxide.

Pioneer-Venus 1992 data showed a CO_2 abundance twice 1979 values at aerobraking altitudes on the night-side. Thus, there was a factor of two bias uncertainty in atmosphere density in addition to expected +-10% orbit-to-orbit random variations superimposed on this 4-day wave phenomenon, if it existed below 170 km. No attempt to model the 4-day wave structure was made due to its uncertain nature. A mean-valued density model was used. The possible bias due to CO_2 abundance uncertainty would be detected during the initial walk-in phase.

Navigation studies indicated random density fluctuations would drive navigation prediction capabilities. These predictions are used by the DSN to tune their receivers and point antennas. They are also used by the spacecraft to control on-board hardware and software events which are sequenced using periapsis-relative timing knowledge uplinked from the ground.

The spacecraft was extensively reprogrammed for aerobraking and could tolerate a 100 second periapsis timing error before risking on-board sequencing conflicts. Studies indicated this was likely to be exceeded in 2-3 days due to the 10% density fluctuations alone. Thus, timing updates based on the latest navigation solution were uplinked once a day. During the last two weeks, the orbit determination process was performed, and results uplinked, twice a day. By comparison, during radar-mapping, Magellan timing errors typically ranged from 0.1 to 0.9 seconds after 6 days.

Navigational studies quantified atmosphere error through mapped covariance studies, in which assumed uncertainties were linearly propagated into the future using the full dynamic model, and Monte-Carlo methods, in which 60 atmosphere models with randomly-varying orbit-to-orbit densities were used to integrate 5-day long trajectories. These were then differenced with the "true" model trajectory to assess error.

6.3   The Venus Gravity Field

Details of gravity field determination are beyond the scope of this paper. In general, the potential was represented by truncating an infinite series to degree and order 21. Gravitational acceleration at any instant could be obtained by computing the gradient of the field-potential expression at a given longitude, latitude and distance from Venus center. To do this for a 21 x 21 field, it is first necessary to solve for 480 constant coefficients.

The set of field-defining coefficients used for aerobraking was the JPL-MGN05 gravity model. It was determined using 437449 selected Doppler measurements from PVO and the first 3 Magellan cycles. A more accurate 60 x 60 preliminary field had been produced by the gravity science group from Cycle-4 data, but comparison studies showed it took navigation software three times longer to execute using this larger field [16]. Prediction accuracy was better, but not enough so as to justify the additional execution time in a tight uplink schedule.

Prediction error due to gravity field imprecision was assessed by comparing a given field's predicted trajectories with actual results from previous cycles over the aerobraking longitudes between 340 and 90 degrees East. Global residual RMS was determined by fitting data at 15 degree intervals around the planet and iterating each fit to convergence. MGN05 yielded converged residual RMS values averaging 0.5053 mm/s over the aerobraking longitudes, 8.2% smaller than the previous navigation field.

7.0   Navigation Aerobraking Operations

Operations during aerobraking required rapid dissemination of results to members of the flight team for reaction and coordination. Navigation obtained new DSN tracking data from the Multi-Mission Navigation group no later than 7:00 a.m. A complete reconstruction of the recent trajectory had to be generated, models updated and a 5-day

prediction disseminated to the project by 10:30 a.m., for analysis and uplink to the spacecraft, and to the DSN for the daily generation of new frequency predicts. It would not have been computationally possible to support this schedule if the faster Sparc-10 CPU had not been released and integrated into the navigation network earlier that spring.

Solutions were also performed in the afternoon. Initially this was so the navigation team could stay current with the tracking data. In the last two weeks, it became necessary to uplink both morning and afternoon results to the spacecraft due to the rapidly changing orbit and unpredictable End-Game density fluctuations. Navigation solutions were necessary 7 days a week to characterize developing trends.

To begin the orbit determination process, an analyst defined an arc of data between 8 and 12 orbits in length, obtained initial state conditions and updated the dynamic modeling. The atmosphere model was modified daily by the navigation team to incorporate the recent mean density conditions. DSN clock offsets were also updated daily based on a least-squares fit of DSN reported offsets over the last 20 days. Data provided by other groups included daily ionosphere calibrations and weekly Earth rotational timing and polar motion models.

Typically, over 100 parameters were estimated from the tracking data for each fit. This included the 6 component position and velocity vector, atmosphere densities during each drag pass and an 8x8 set of local gravity field coefficients. Attitude control thruster firings near each periapsis were modeled and solved for as constant accelerations. Dynamic pressure was computed from the solved-for densities and the solved-for velocity vector.

The estimation algorithm was constrained by a set of assumed uncertainties. State vector 1-sigma uncertainties were 3.2 km on x and y components, 1 km on the z-component. Velocity component 1-sigma was 1 m/s. An 8 x 8 variance vector constrained local gravity solutions. This array had been gradually developed during previous cycles by linearly scaling the formal covariance produced from an early field estimate. This calibration adapted the optimistic formal covariance to account for known and unknown error sources affecting the gravity field estimate. Atmospheric density 1-sigma was typically taken to be 15% of the current LST density based on daily nav-team trending of previous results. AACS thruster firing 1-sigma was taken to be 5% of the mean nominal values reported daily by the spacecraft team. When solving for COTMs, burn force uncertainty was taken to be 6% while right ascension and declination 1-sigma errors were assumed to be 0.003 degrees.

7.1   Operational Challenges

Complicating factors included the unscheduled loss of a scheduled tracking station one week after aerobraking began, when it went out of service for 2.5 months pending replacement of the polar bearing. This resulted in occasional 8 hour tracking gaps and the loss of differenced

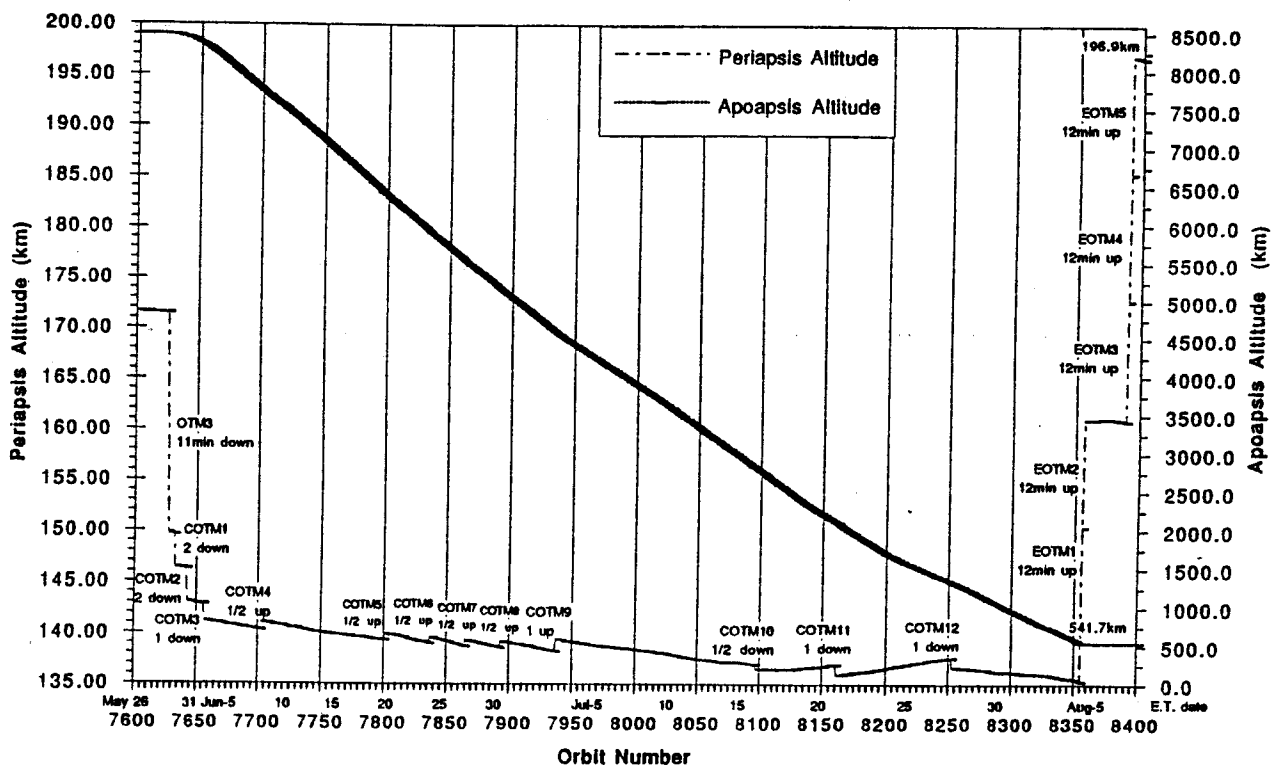## Magellan Orbit Altitudes during Aerobraking

Fig. 2 Apses altitudes during aerobraking. The right-hand label scales the smoothly decreasing apoapsis altitude. The purpose of aerobraking was to effect this change. The left-hand scale shows the periapsis altitudes used to control drag decleration. Discontinuities in periapsis altitude mark thruster firings used to maintain position in dynamic pressure corridor.
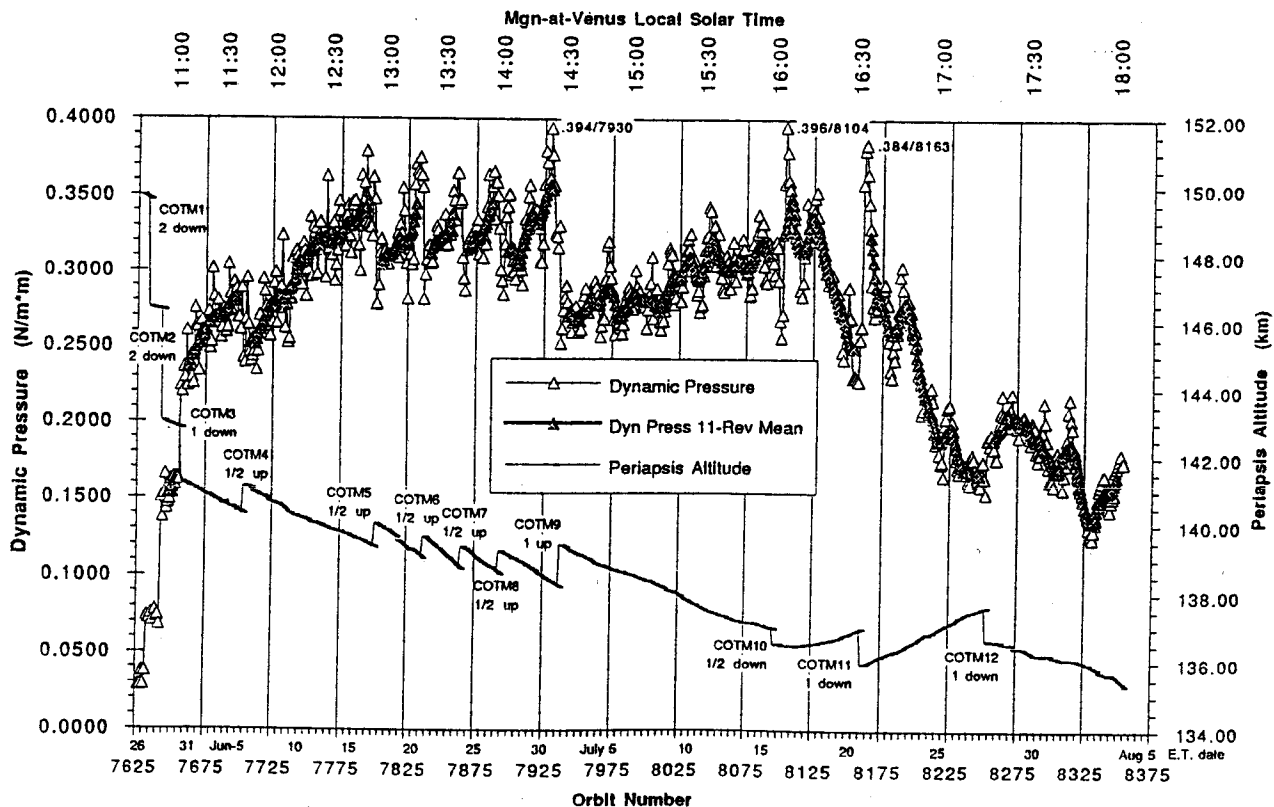
Venus Atmosphere Dynamic Pressures during Magellan Aerobraking

Fig. 3 Dynamic pressure during aerobraking. Determined from Doppler tracking data, this quantity was closely related to spacecraft temperatures. It was monitored to determine maneuver placement and aerobraking efficiency. An 11-rev mean value is superimposed to reveal trends. The largest dynamic pressure experienced by Magellan was 0.396 N/m^2 on orbit #8104.

Atmospheric Density vs. Time
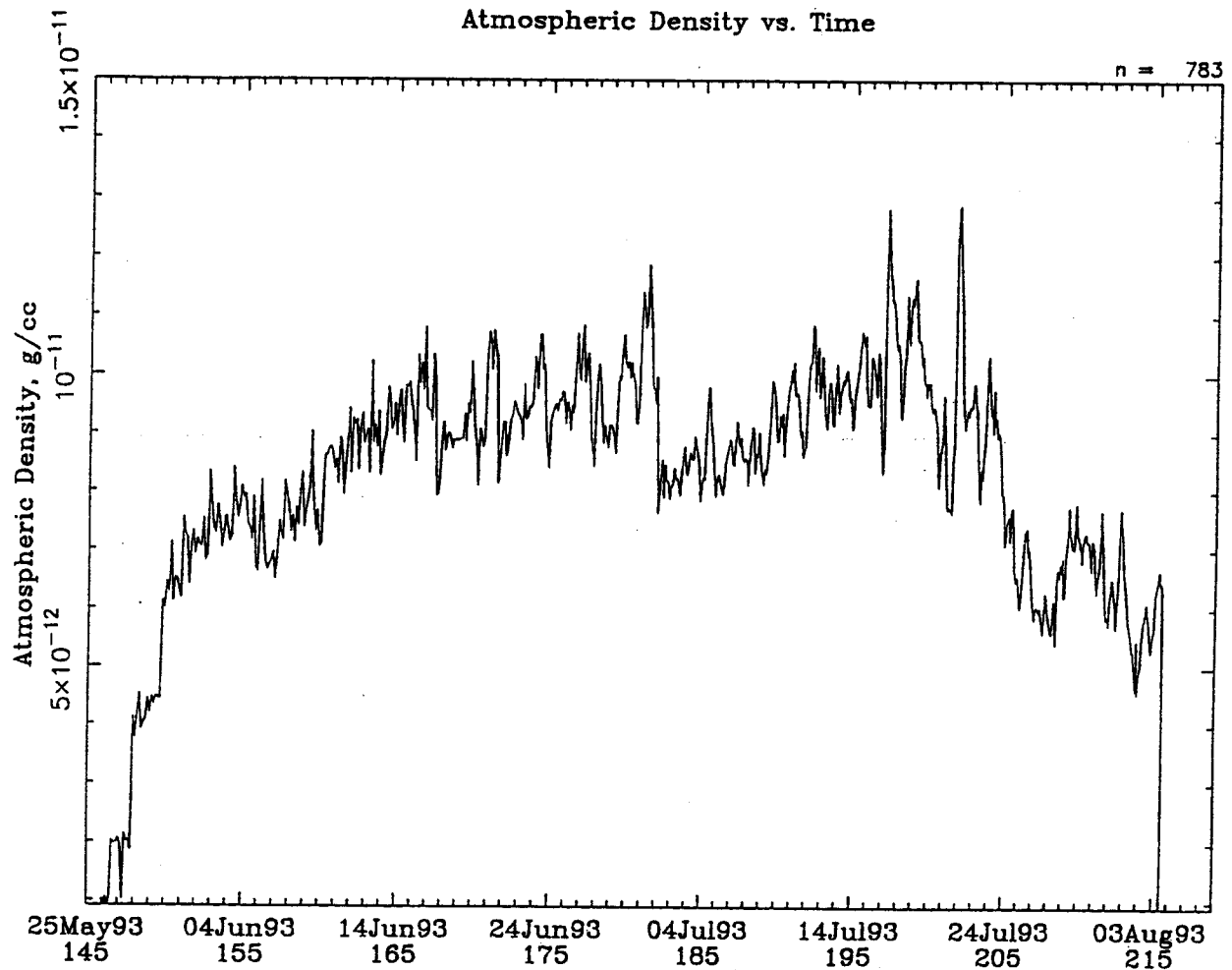
Fig. 4   Atmospheric density at altitude for Magellan aerobraking (determined from radiometric Doppler tracking data).
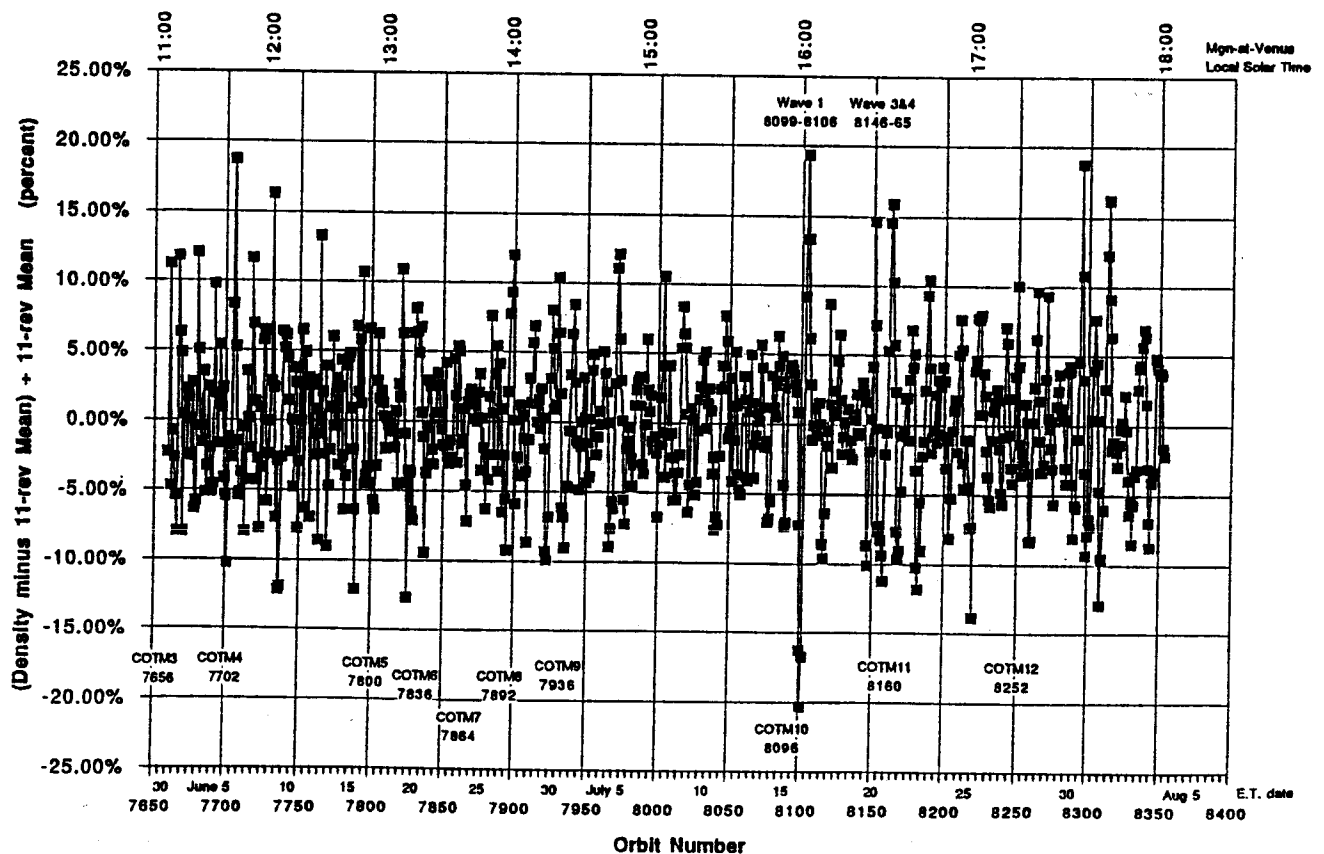
Fig. 5   Atmosphere density variability during Magellan aerobraking. This is represented by the percentage difference of a drag-pass density with an 11-rev running mean density. 1-sigma scatter was 4.78%, from 11:00 to 16:00, and 5.91% thereafter as the spacecraft approached the much more variable night-side atmosphere. For the entire interval, 1-sigma was 5.22%, about half the variability seen at higher altitudes between 170 and 180 km, at the same Local Solar Times, during Cycle-4.
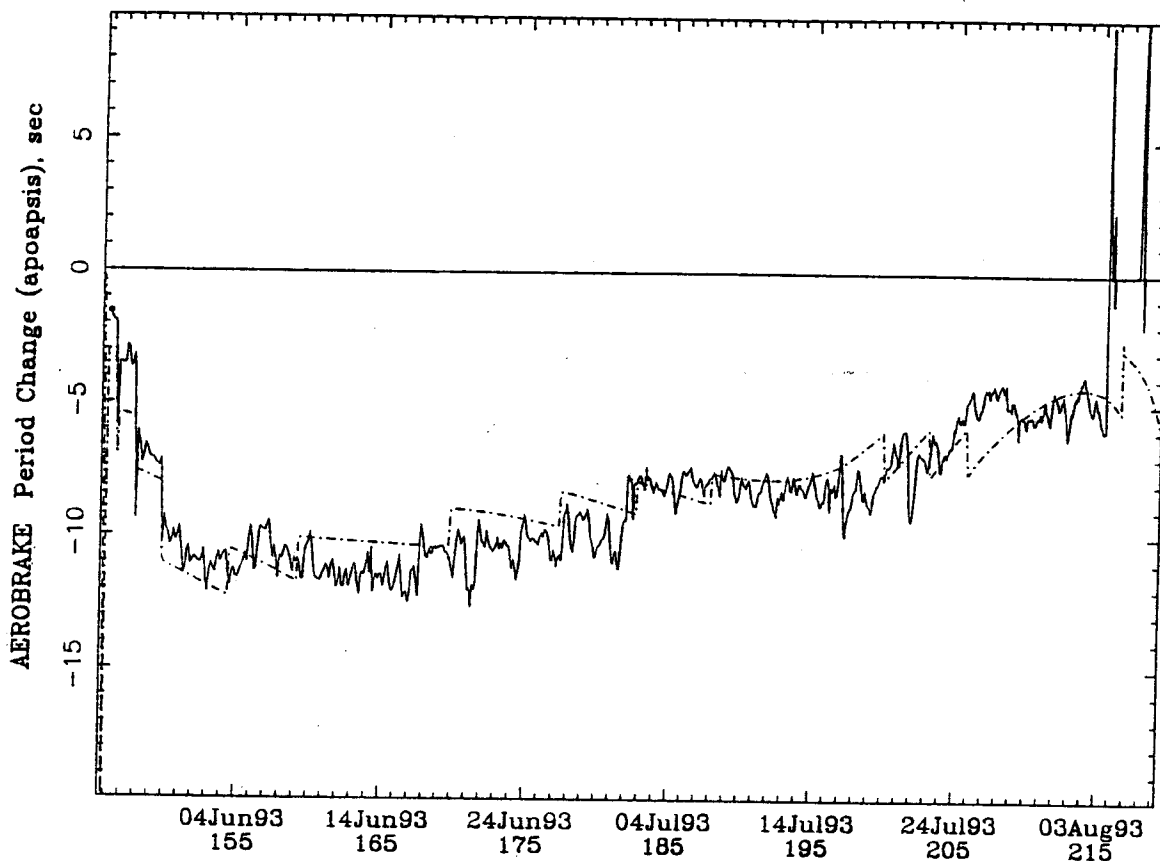
Fig. 6   Orbital period change during aerobraking. The broken line was the nominal baseline prediction shortly before the start of the maneuver. The solid line shows actual results.

Magellan Aerobraking Periapsis Timing Error
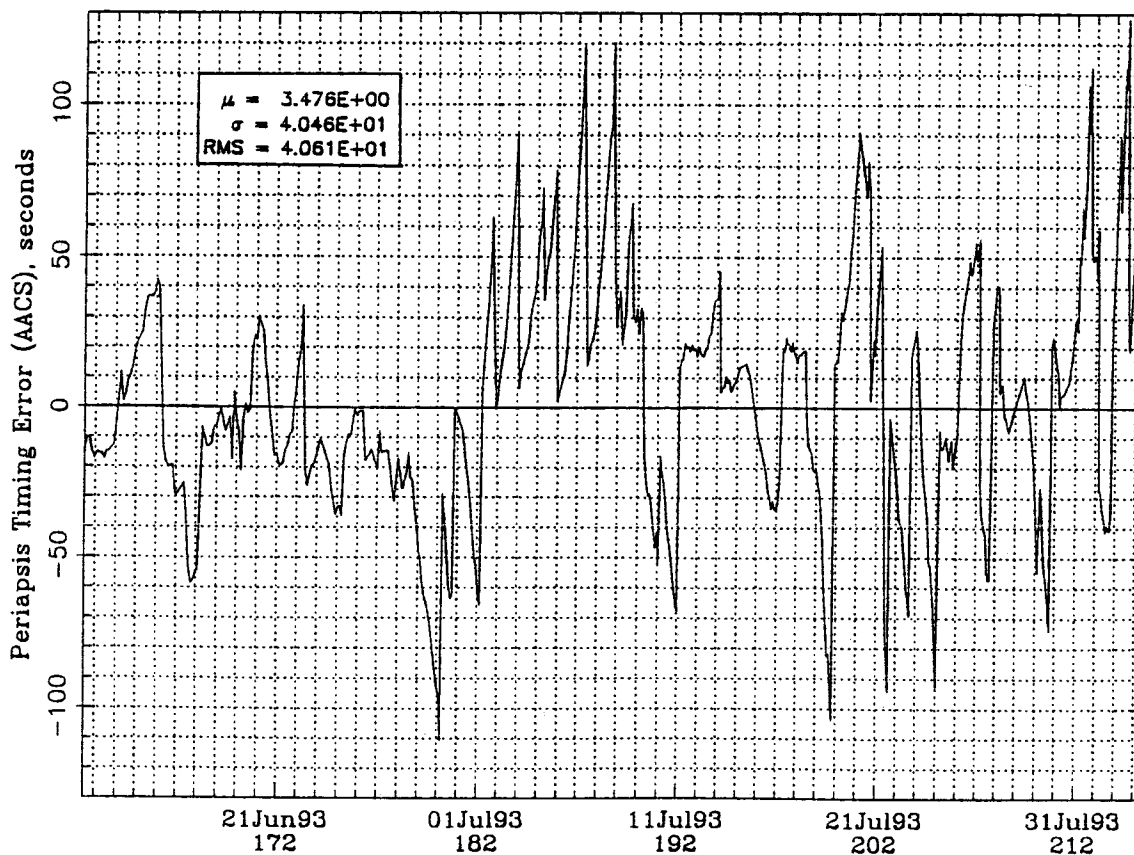
Fig. 7   Periapsis timing error is the difference between the spacecraft's assumed (predicted) periapsis time, based on navigation data uplinked from the ground, and reconstructed periapsis times derived from spacecraft attitude control telemetry.   These values necessarily include attitude determination error as well as navigation error and have 1-sigma uncertainty of about 8.8 seconds.
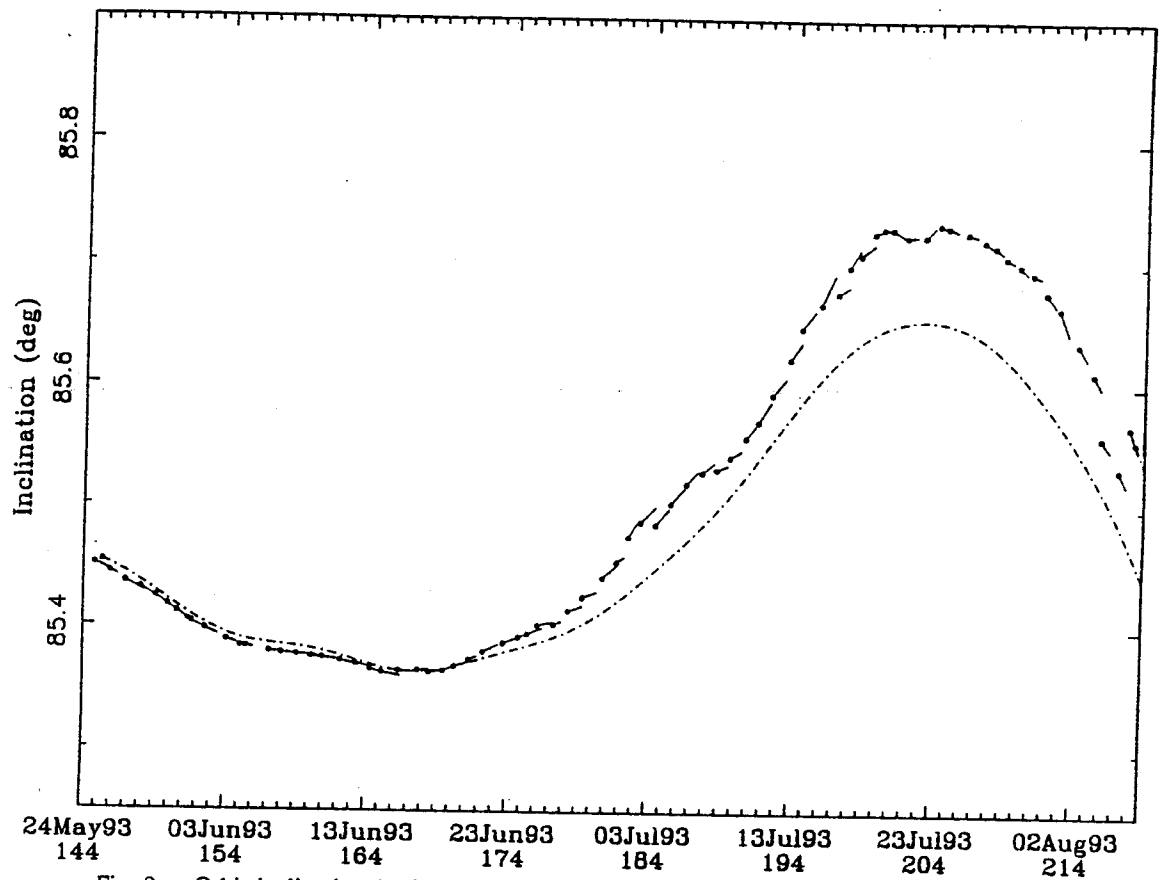
Fig. 8 Orbit inclination (solid) versus baseline prediction (dashed line). Deviation is due to gravity field mismodelling and unmodelled out-of-plane forces such as slightly misaligned thruster firings and atmospheric rotation perpendicular to the spacecraft orbital plane. Dots are initial state epochs.
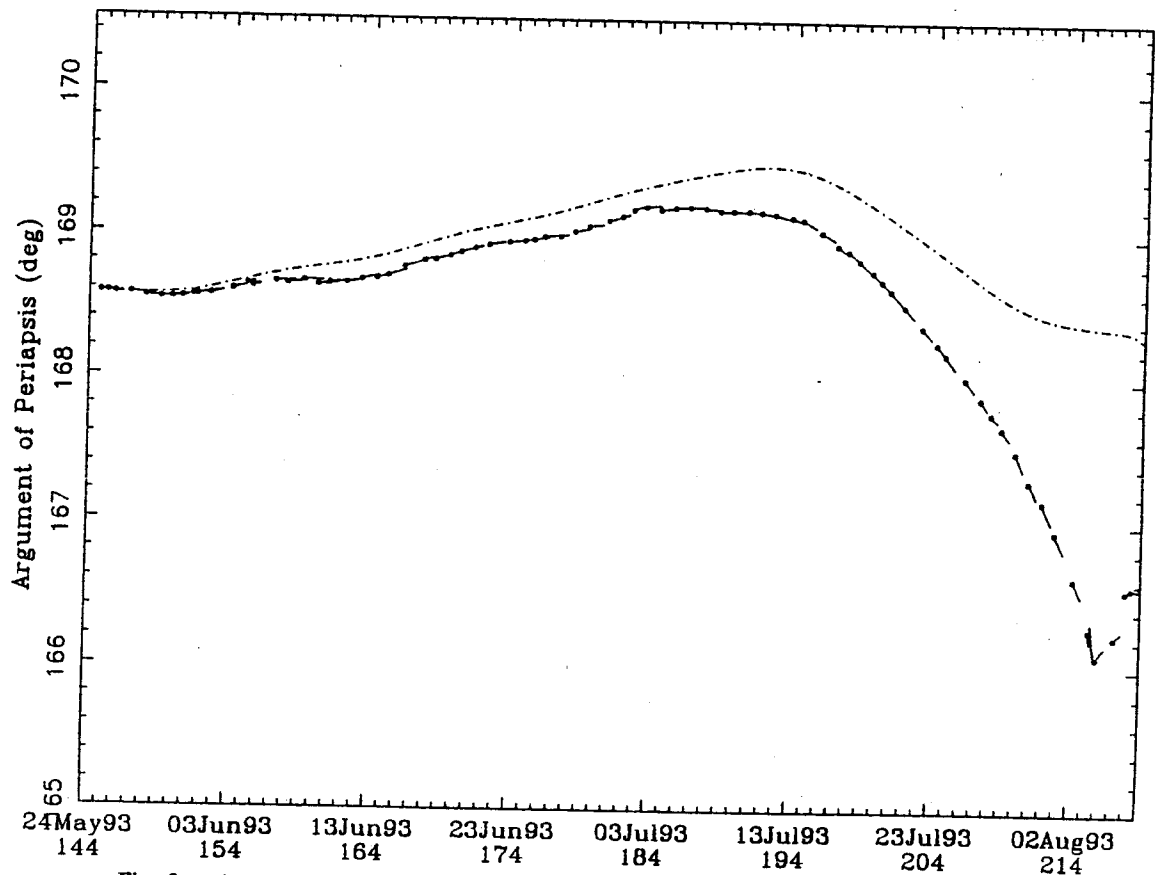
Magellan Aerobraking Argument of Periapsis

Fig. 9 Argument of periapsis (solid) vs. baseline prediction (dashed line). The increasing deviation near the end is due to post-periapsis AACS thruster firing induced rotation of the line-of-apsides as the orbit became more nearly circular. Dots are state epochs.

Doppler data, when an alternate antenna could not be allocated. In addition, DSN sites world-wide were phasing in a new software/hardware upgrade that subtly and unpredictably corrupted Magellan's frequency-ramped tracking data. It was necessary to iteratively "build" a fit by adding tracking data one pass at a time so as to identify the corrupted measurements. The number of strong forces affecting spacecraft motion during aerobraking made distinguishing corrupt data from a dynamic signature somewhat problematic.

Up to half of Magellan's tracking data had to be deleted until the upgrade was removed from DSN sites, after one month of unsuccessful debugging. This was a substantial operational burden and degraded prediction accuracy. The loss of data was most keenly felt during the first three weeks when Magellan's orbit plane, as seen from Earth, was in a "face-on" geometry. In such a relative position, spacecraft motion is perpendicular to the line of sight, reducing the information content of line-of-sight Doppler measurements to near zero.

Lack of information about attitude control thruster firings around periapsis also affected navigation procedures. The burns occurred in the 10 minute interval after periapsis passage. Errors in modeled thruster firing times and magnitudes would propagate into the prediction, changing future periapsis times, causing the model to become increasingly out of sync with actual thruster activity. The delta-v immediately after periapsis had the effect of decreasing the semi-major axis and orbital period, while altering the specific angular momentum vector. Errors in model-predicted periapsis times of up to 40 minutes would accumulate at the end of a 5 day prediction, if not compensated for.

It was thus necessary to iterate the daily five-day predictions (and weekly two-week predictions) by integrating a trajectory with a nominal constant acceleration model. New periapsis times would be obtained from this first trajectory, a new acceleration model constructed and a new trajectory integrated with this new model. This was repeated 3-4 times until the final iteration yielded periapsis times within 2 seconds of the previous iteration. The ability to specify periapsis-relative (instead of absolute) time acceleration models would have substantially reduced the navigation burden, but there was insufficient time to implement this software modification.

Results of the morning navigation fit (and spacecraft telemetry) were reviewed by the Aerobraking Planning Group, composed of representatives of the Mission Planning, Spacecraft and Navigation teams. Strategy changes and COTM placement were discussed. Recommendations were prepared for the daily 1:00 p.m. Mission Director meeting. At this meeting, representatives of all teams presented their latest results. New strategies were discussed and approved.

8.0 Aerobraking Performance and Results

Aerobraking was initiated May 25, 1993 when a 674-second burn at apoapsis (OTM-3) lowered periapsis altitude from 171.3 km to 149.7 km. Fig. 2 shows periapsis and apoapsis altitudes for the subsequent 70 day aerobraking interval. Over the next four days, three walk-in maneuvers stepped the spacecraft deeper into the atmosphere. It became evident that densities were more consistent with the "single-CO_2" model at 10:30 a.m. LST.

Once the dynamic pressure corridor was located below 140.7 km, navigation focused on characterizing atmosphere density trends to update the atmosphere model, predicting COTMs necessary to remain in the corridor and periodically propagating the trajectory into the future to re-examine the End-Game. It was desirable to aerobrake as much as possible in the early phases so that a more conservative End-Game, without COTMs, could be implemented.

Mean density during the initial phases was 22% higher than predicted by the nominal single CO_2 model. However, by the second week, it became apparent there was sufficient temperature margin on the HGA and in the AACS control of aerodynamic torques that the dynamic pressure limit could be increased to 0.35 N/m^2. Fig. 3 shows dynamic pressure over the entire aerobraking interval.

Orbit-to-orbit density variations were half that observed during Cycle-4. Fig. 4 shows the atmosphere density during aerobraking and Fig. 5 the orbit-to-orbit variations relative to an 11-rev mean density. The 4-day density wave observed at 170-180 km was not evident at the aerobraking altitudes 40 km lower, although unpredictable long-term fluctuations did exist. True airspeed varied from 30700 kph (19100 mph) at the start of the aerobrake to 26600 kph (16500 mph) at the end.

Perusal of these graphs will reveal major aerobraking events. In the free-molecular flow regime, at aerobraking altitudes between 136 km and 143 km, Magellan experienced a drag force that varied from 0.6 to 2.0 pounds distributed over a 23 m^2 surface area. As a result, orbit period was typically decreased from 5 to 12 seconds per orbit during most phases of the maneuver. Fig. 6 shows a plot of actual period change versus the initial baseline plan. It can be seen from this graph that mean period change was slightly less than planned during the first two weeks of aerobraking, due to the smaller Walk-In densities, and slightly more than planned thereafter, as Project strategy was revised to compensate. Apoapsis altitude decreased between 6 and 15 km per orbit during the main phase, or about 110 km per day.

Periapsis prediction performance during the last 495 aerobraking orbits can be assessed from fig. 7. This plot shows spacecraft-team computed periapsis timing errors. They were obtained by differencing uplinked navigation predictions with telemetry-based reconstructions of the mean attitude error on the spacecraft body-fixed X-axis. The reconstructed timing deltas have a 1-sigma uncertainty of 8.8 seconds [17].

Ten drag passes exceeded the 100-second specification during this time interval, six by more than measurement uncertainty; typically this was the last pass

before new timing data was scheduled to be uplinked. Mean timing error was +3.47 seconds with a 1-sigma spread of 40.5 seconds. No significant systematic bias is evident in the timing error performance, with the 40.6 second RMS being nearly equal to 1-sigma over this sub-interval.

Twelve COTM maneuvers were required for corridor maintenance. A thirteenth was twice planned but subsequently canceled when dynamical trends developed that rendered it unnecessary.

Figs. 8 and 9 show the evolution of two classical orbital element parameters, inclination and argument of periapsis, during aerobraking. Inclination is of interest since drag along the direction of motion would not be expected to alter the angle of the orbital plane with respect the equator. Deviation of actual inclination from the initial baseline plan thus reveals unmodeled forces acting perpendicular to the direction of motion. Likely forces include gravity field mismodeling, slightly misaligned thruster firings (both COTM and AACS), and the rotation of the Venusian atmosphere perpendicular to the orbit plane of the spacecraft. The argument of periapsis plot reveals the rotation of the line-of-apsides as the orbit becomes more nearly circular, due to the unexpectedly asymmetrical attitude control thruster firings in the 10 minutes after each periapsis.

Aerobraking was completed the morning of August 3 when the first of five EOTMs raised periapsis out of the aerobraking corridor. The second EOTM was performed on the next orbit. Final circularization took three more consecutive burns on the 5th. Only 37.8 kg of fuel was required to lower apoapsis 7927 km. This was 60% of the allocated amount and 4.2% of the amount required to do such a maneuver propulsively. The initial final orbit had dimensions of 197 x 541 km.

The spacecraft was apparently undamaged by 730 high-velocity passes through the atmosphere of Venus. In fact, cooler post-aerobraking temperatures indicate the spacecraft was effectively "scrubbed" clean of a surface darkening contaminant that had caused temperatures to run hotter than expected since the cruise to Venus four years earlier.

9.0   CONCLUSION

The Magellan result, with limited ground support resources and a spacecraft not designed for the job, demonstrates the practical efficiencies of interplanetary aerobraking in a relatively unknown planetary atmosphere. The complex dynamics of this maneuver provided a navigational extreme case that tested the limits of the DSN tracking support and traditional orbit determination methodology, further establishing the capabilities of both.

Magellan has since entered a new mission phase, Cycle-5, devoted to high resolution gravity mapping from its near-circular orbit. The project has been down-sized to less than 35 people, the "Lean Mean Gravity Team". Their efforts will continue through April of 1994. If additional funding is forthcoming, one additional 8-month cycle of gravity coverage is desirable before project close-out.

Having returned more science data than all other planetary missions combined, while accomplishing its own set of extraordinary firsts, Magellan has earned its place on JPL/NASA's list of venerable missions.

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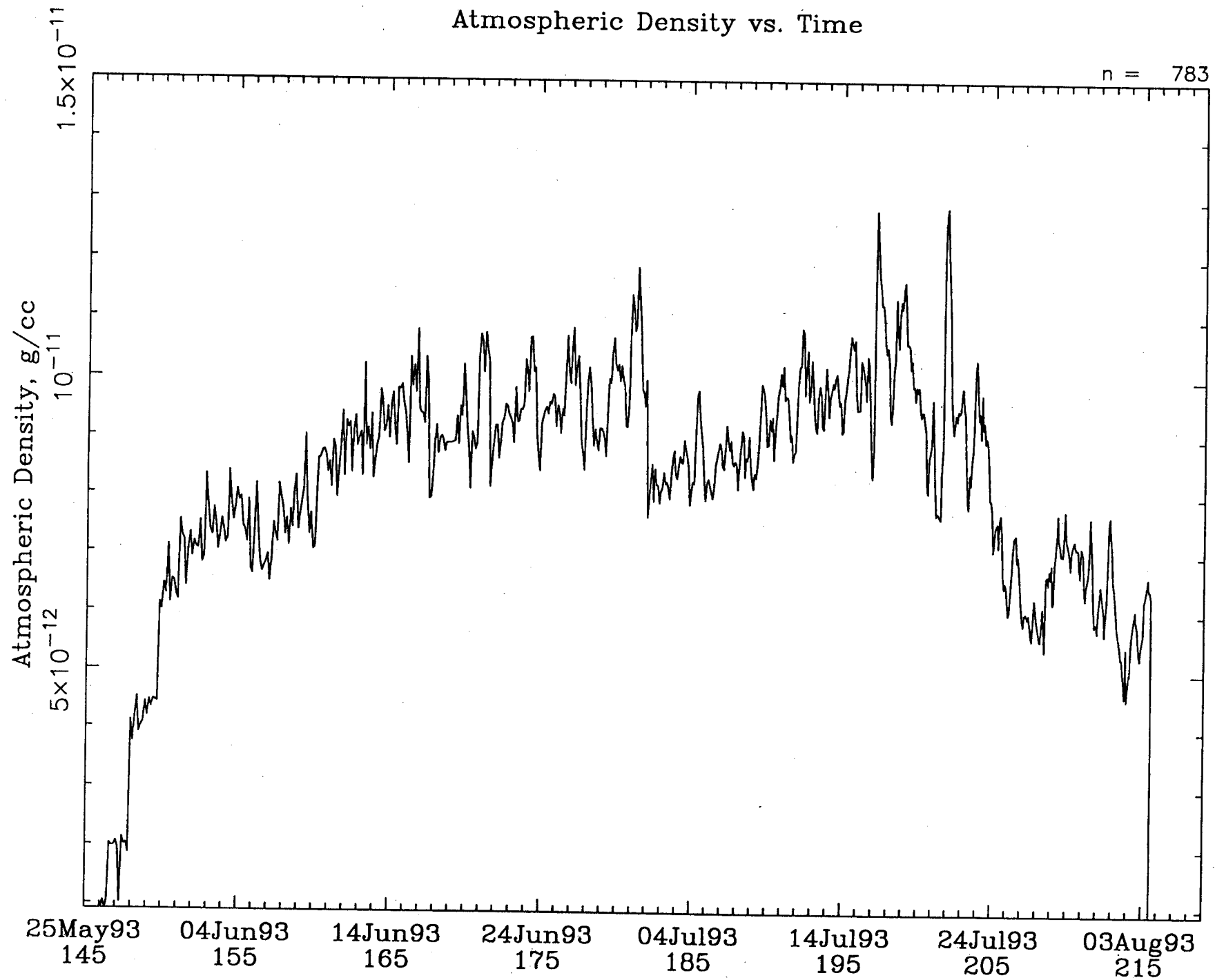
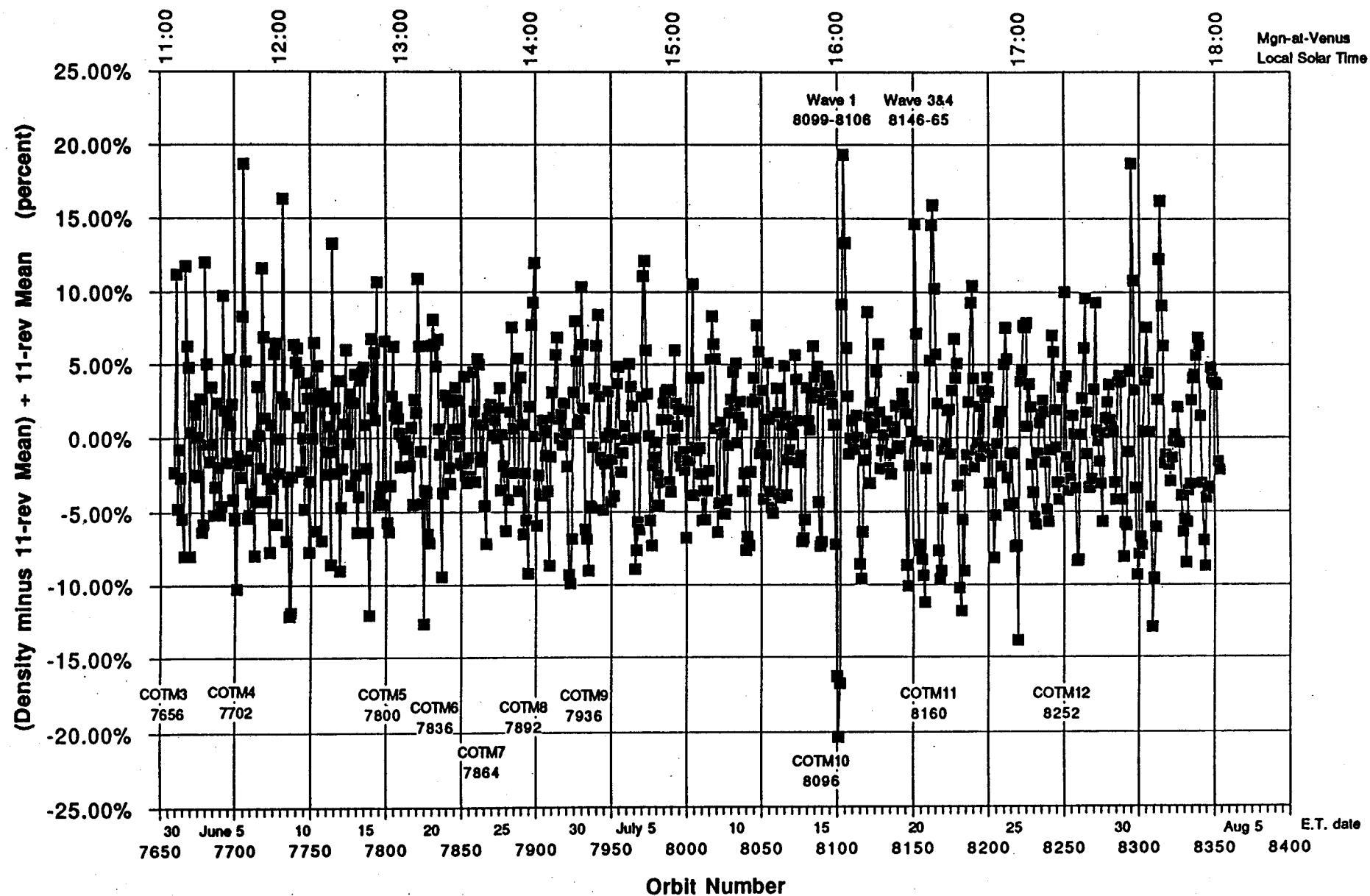# Magellan Orbit Altitudes during Aerobraking
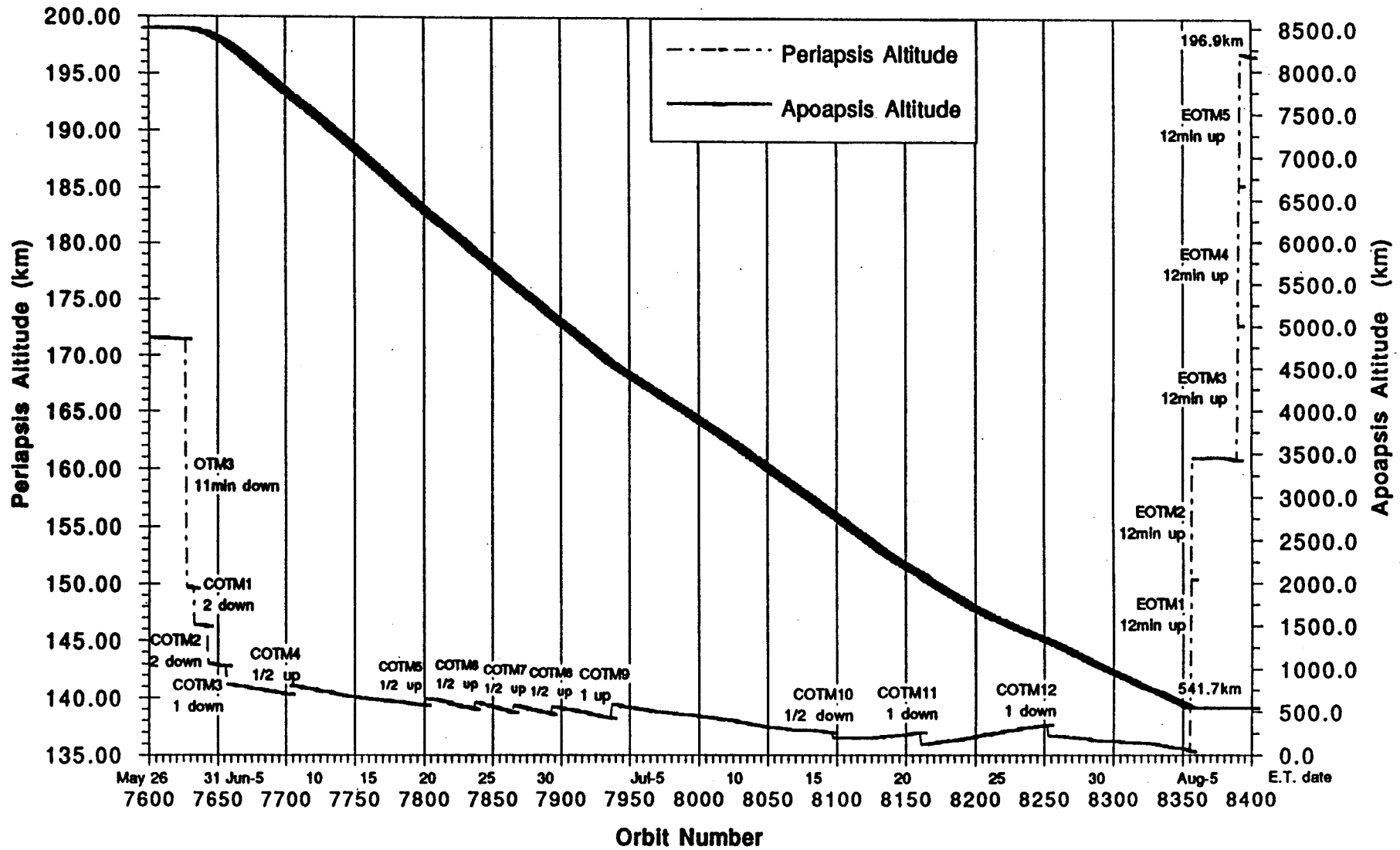
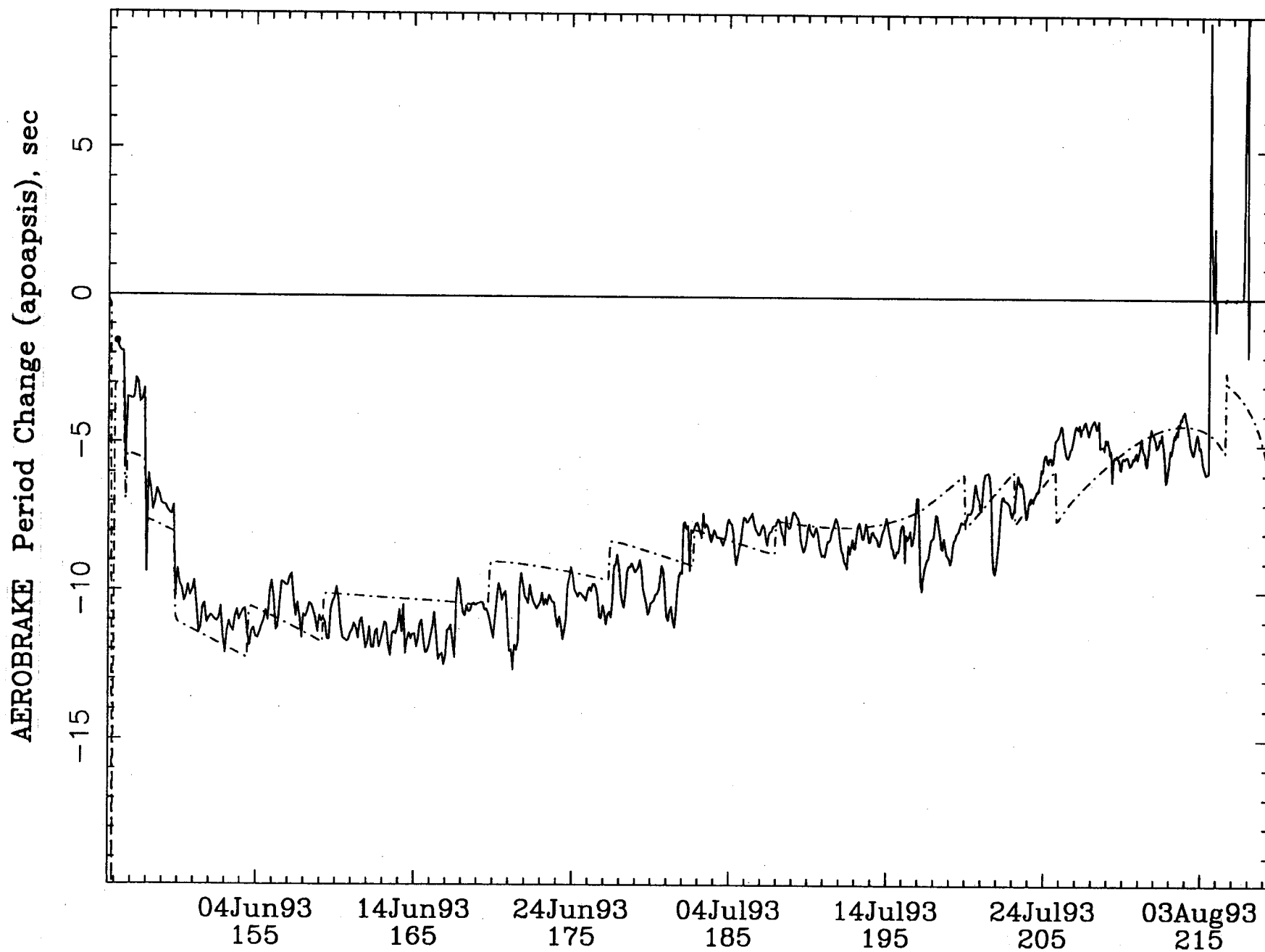# Venus Atmosphere Dynamic Pressures during Magellan Aerobraking
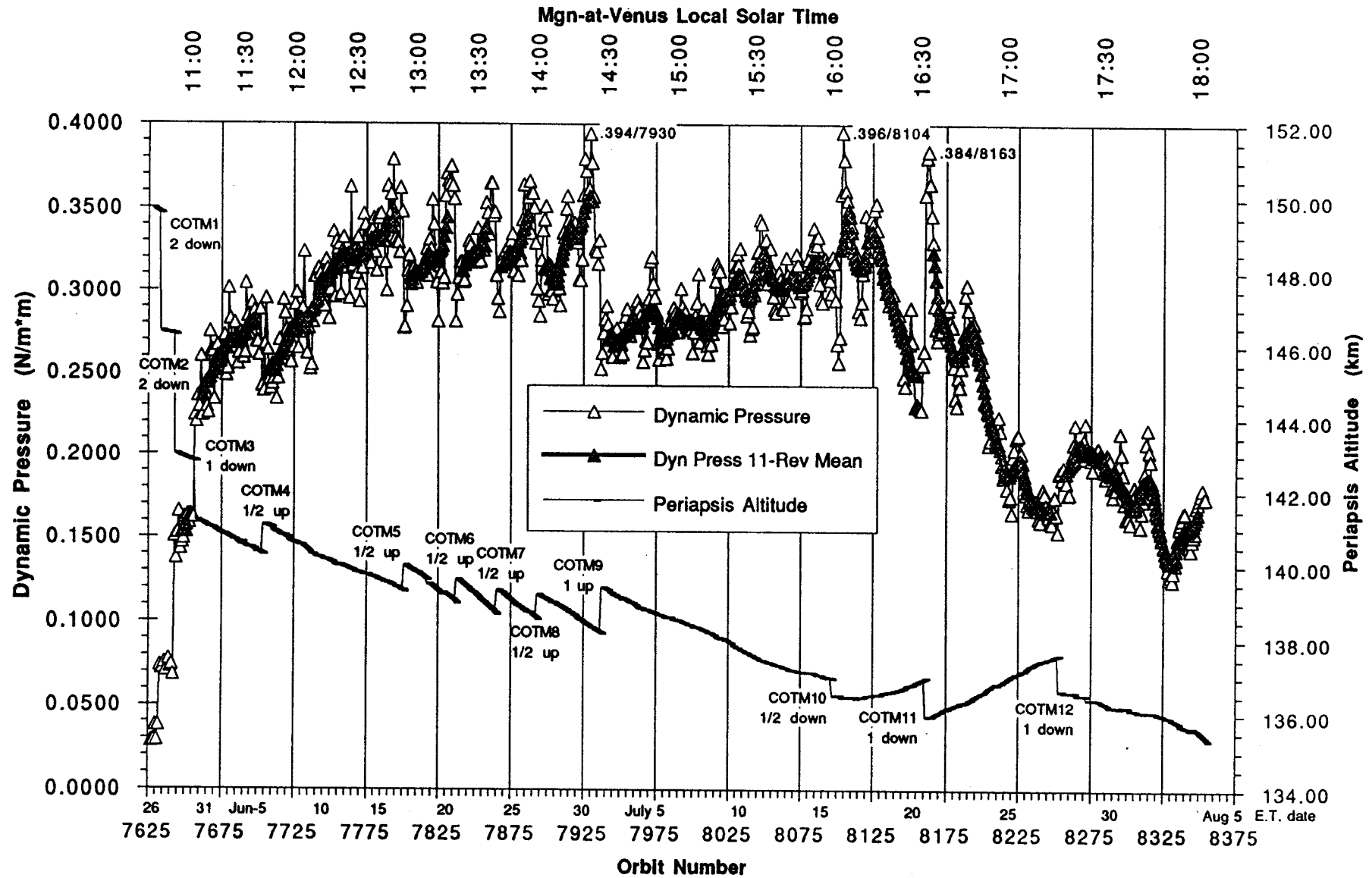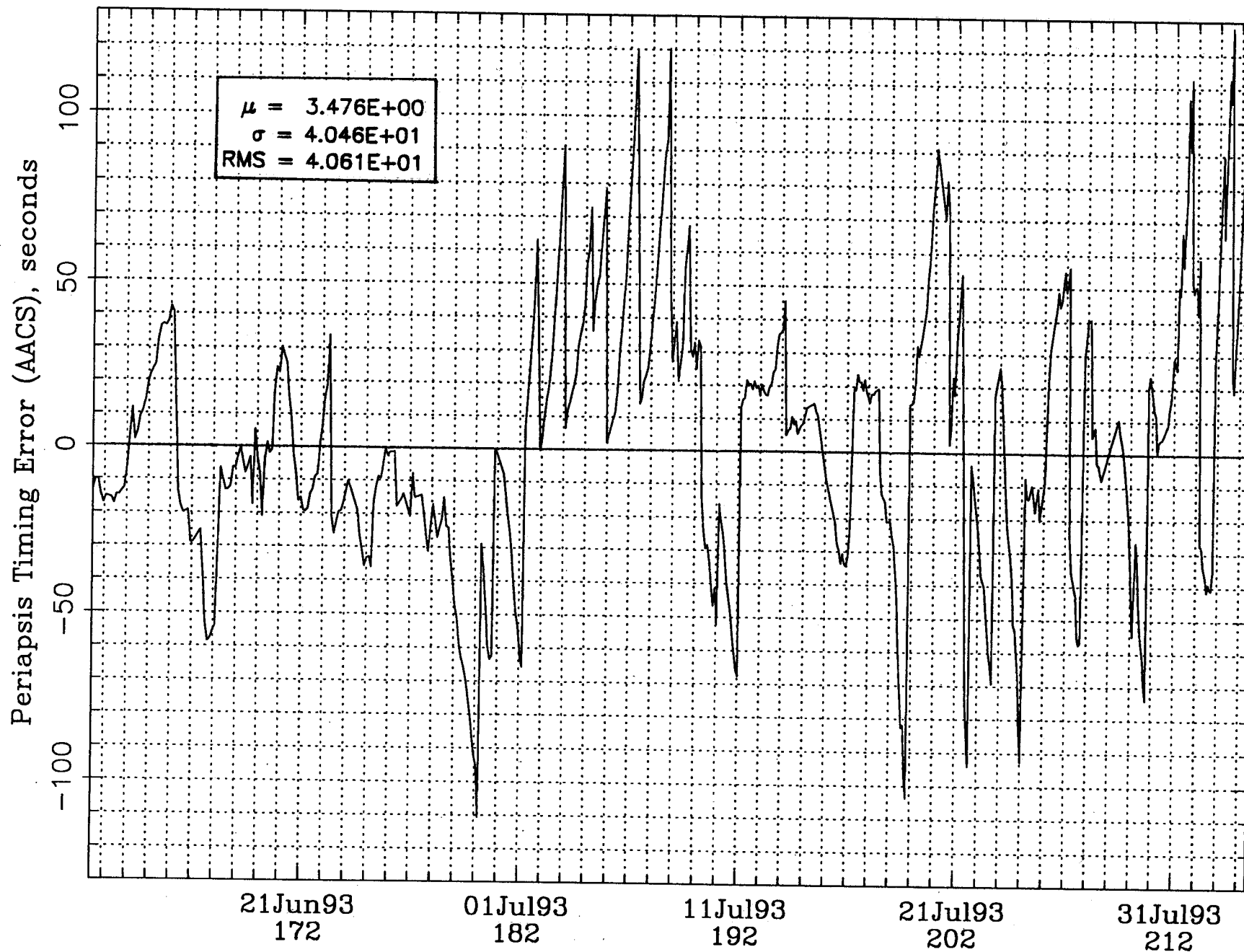
Atmospheric Density vs. Time

Difference between Density and Density 11-Rev Running Means after COTM3
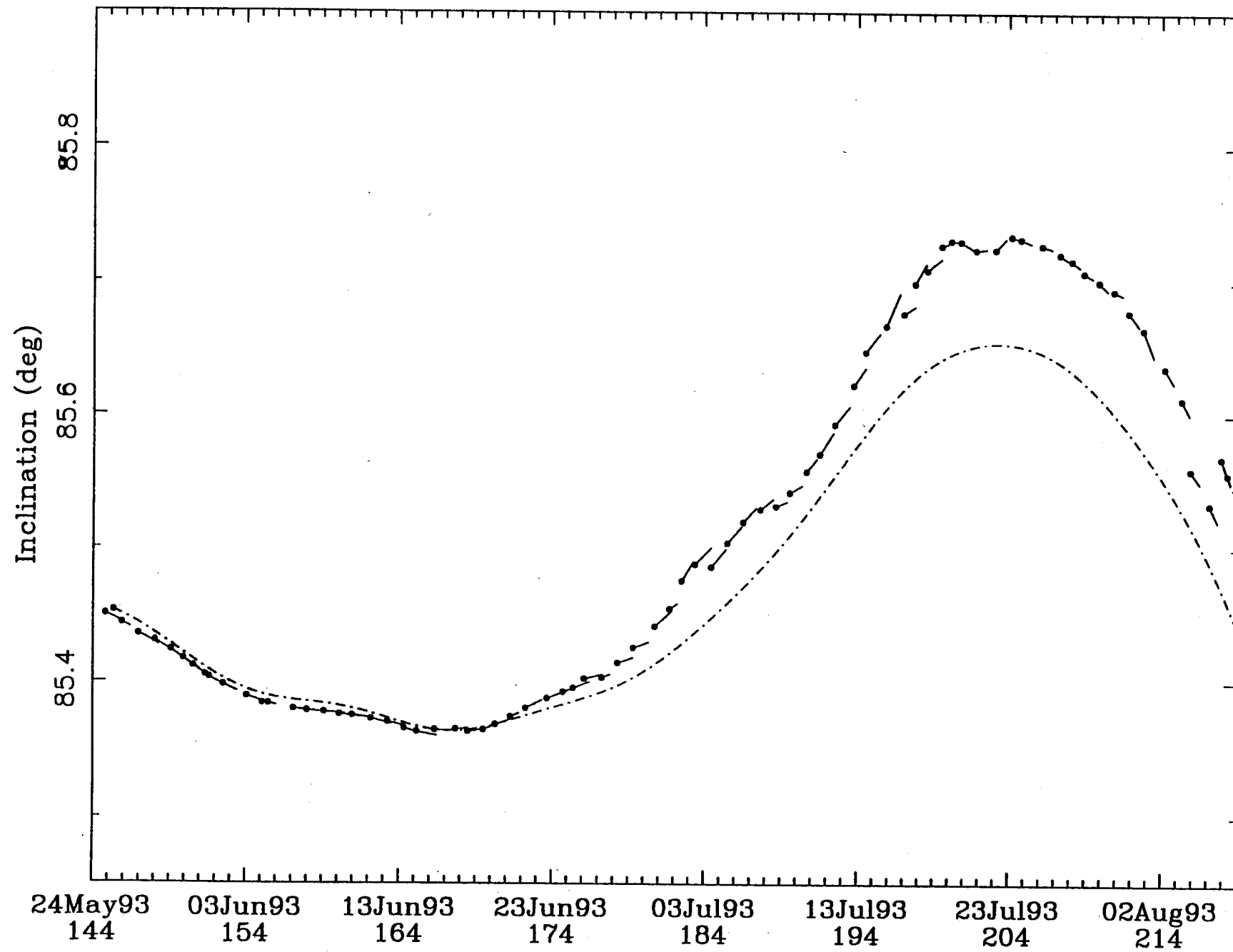**(density scaled to 131 km)**

Magellan Period Change (apoapsis)

Magellan Aerobraking Periapsis Timing Error

μ = 3.476E+00
σ = 4.046E+01
RMS = 4.061E+01

Periapsis Timing Error (AACS), seconds

100
50
0
−50
−100

21Jun93
172

01Jul93
182

11Jul93
192

21Jul93
202

31Jul93
212

Magellan Aerobraking Inclination

Magellan Aerobraking Argument of Periapsis